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# Evaluation of the Effect of Ship Motion on Propeller Performance

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## Abstract

Due to the environmental regulations, the fuel efficiency in seaway becomes more important. In this paper, the effect of ship motion on propeller performance will be evaluated. The influence will be divided into two different factors. The first one is the influence due to ship positions in seaway and the induced velocity due to wave itself, and the second one is the interaction between the ship hull and the propeller. The influence of the ship motion to the propeller performance is then the sum of these factors. In this paper, the first factor is considered as mainly the potential flow factor, and the second one is considered as mainly the viscous flow factor. We have assumed these factors are independent to each other in this paper. For the effects of ship positions and the influence of wave itself, a potential flow propeller unsteady flow boundary element method is used with a ship motion prediction program for computations. For computing the interactions between the ship hull and propellers, the viscous flow RANS method is adopted. Instead of using the real propeller geometry in RANS computations, the body forces will be used to represent the propeller effects, and it is called the body force method. A computational example is demonstrated to show that the body force method can successfully simulate the interaction between the ship hull and a propeller. Computational examples are also demonstrated for investigating the effects of ship positions in seaway on the propeller performances. In this paper, we have established the first step to integrate ship motion computational method, the propeller boundary element method, and the viscous flow RANS method to evaluate the propeller performance in seaway.

**Keywords:** propeller in wave, ship motion, Boundary Element Method, RANS, body force

## 1 Introduction

Due to the environmental regulations, the fuel efficiency in seaway becomes more important. In this paper, the effect of ship motion on propeller performance is evaluated, and the influence is divided into two different factors. The first one is the influence due to ship positions in seaway and the wave induced velocity, and the second one is the interaction between the ship hull and the propeller. The influence of the ship motion to the propeller performance is then the sum of these two factors. In this paper, the first factor is considered as the potential flow factor, and the second one is considered as the viscous flow factor.

The propeller performance in waves has been studied by many researchers. Journée (1976) applied an approximate method to study the ship motion effects to the propeller performance, and he has also carried out experiments to make the comparison. Faltinsen (1980) has investigated the resistance and propulsion in seaway, and he claims that since the encounter frequency of the incoming wave is far smaller than the propeller rotational frequency, only the vertical velocities due to motions are critical to the propeller performance in waves. The variation of the propulsion thrust in wave can be computed by quasi-steady flow method, that is, to solve the thrusts at different time step, and the thrust in wave will be the mean value of these. Stuart and Boswell (1982) investigated the pitch motion to the propeller loadings by experiments, and they found that the loading variations to motions can be obtained from linearly superposition of loading variations at different frequencies. Stuart (1996) has also carried out experiments to study the propeller cavitation in waves. Nakamura (1975) and Naito (1979) also studied the propeller loading variations in seaway by experiments, and they concluded that the wave induced velocities and propeller immersion depth have critical effects to the propeller loading variations in waves. They have also derived approximate formula for this problem. Nakatake (1986) later developed a panel method using source and sink distributions to simulate the ship hull, propeller and rudder, and studied the interactions of hull/propeller/rudder by computations. Ando (1989, 1990) has verified the above computations by experiments. Recently, Kashiwagi (2004) investigated the propeller performance in waves by using the Enhanced Unified Theory (EUT), which is derived from ship motion theory. Paik (2008) has measured the propeller flow field at different immersion depth using PIV, and Chuang (2011) has studied the power and speed loss in waves by experiments.

In this paper, the effects of ship positions and the influence of wave itself are considered to be dominated by the potential flow effects, and the interaction between the ship hull and the propeller is considered to be dominated by the viscous flow effects. We will assume these effects are independent to each other in this paper. For the effects of ship positions and the influence of wave itself, a potential flow propeller unsteady flow boundary element method is used with a ship motion prediction program for computations. The influences from ship positions are computed by the ship motion program, and then transfer into the propeller inflows. The unsteady flow propeller boundary element method is then used to compute the propeller forces in this time varied inflow. For investigating the interaction between the ship hull and propellers, the viscous flow RANS method is adopted. Instead of using the real propeller geometry in RANS computations, the body forces will be used to represent the propeller effects.

Two different computational methods are used in this paper, and they are the potential flow propeller boundary element method, and the viscous flow RANS method with a body force model. We will describe these two methods next.

## 2 The Unsteady Flow Propeller BEM

The unsteady flow propeller boundary element Method (BEM) used in this paper is a perturbation potential based boundary element method, and the governing equation is:

$$2\pi\phi_p(t) = \int_{S_P} [\phi(t)\frac{\partial G}{\partial n} - G\frac{\partial \phi}{\partial n}(t)]dS + \int_{S_W} \Delta\phi(\vec{x},t)\frac{\partial G}{\partial n}dS] \quad (1)$$

In equation (1), the coordinate system is fixed on the propeller, $S_B$ denotes the propeller blade surface, and $S_W$ denotes the propeller wake surface. $G$ is the Green function, $1/r$, $r$ is the distance between the panel point and the induced point $p$, and $n$ is the normal vector. The Green function $G$ can also be explained as the potential induced by a unit strength source, and $\partial G/\partial n$ can be explained as the potential induced by a unit strength dipole. $\phi(t)$ is the strength of perturbation potentials, or equivalent to the dipole strength. $\partial\phi/\partial n$ is the source strength, and it can be determined by the boundary condition:

$$\frac{\partial \phi}{\partial n}(t) = -\vec{U}_{in}(\vec{x},t)\bullet\vec{n} \quad (2)$$

$\vec{U}_{in}(\vec{x},t)$ is the inflow velocity relative to the propeller, and it is a function of position and time. We will discuss the inflow velocity later. $\Delta\phi$ is the dipole strength in the wake from the Kutta condition, and the source strength in the wake is zero since the wake has no thickness. The dipole strength in the wake is the difference of the dipole strength at upper and lower trailing edge panels from Kutta condition. The discretized form of the equation (1) is

$$\sum_{j=1}^{N_P} a_{i,j}\mu_j^n + \sum_{m=1}^{M} W_{i,m,l}\Delta\phi_{m,l}^n = RHS_i^n; \quad i=1,N_P \tag{3}$$
$$RHS_i^n = \sum_{j=1}^{N_P} b_{i,j}\sigma_j^n - \sum_{m=1}^{M}\sum_{l=2}^{N_w} W_{i,m,l}\Delta\phi_{m,l}^n$$

In equation (3), $N$ is number of panels chord-wise, $M$ is number of panels span-wise, and $N_P$ is total number of panels, $N_P=N*M$. $N_W$ is number of panels chord-wise in the wake. $\mu_j$ and $\sigma_j$ represent the discrete forms of $\phi$ and $\partial\phi/\partial n$, and $a_{i,j}$ , $b_{i,j}$ represent the discrete forms of the integrations of $\partial G/\partial n$ and $1/r$ over a panel. $a_{i,j}$ and $b_{i,j}$ are defined as the "influence function" of dipole and source respectively from panel $j$ to collocation point $i$. $W$ represents the discrete forms of the integration of $\partial G/\partial n$ over a wake panel. The superscript $n$ denotes the time step, and time $t$ is defined as $t=n\Delta t$. A time marching numerical scheme is adopted for the solution, and the inflow velocity is updated at each time step. The numerical procedure is described as follows:

1. The inflow velocity, $\vec{U}_{in}(\vec{x},t)$, is different at each time step.
2. The source strength, $\sigma_j^n$, is thus different at each time step (equation (2)).
3. The dipole strength, $\mu_j^n$, can then be solved at each time step from equation (3).
4. The wake dipole strength, $\Delta\phi$, can then be updated at each time step.
5. Steps 2 to 4 are iterated until the solutions are converged.

The boundary condition of the presented boundary element method is determined by the inflow velocity $\vec{U}_{in}(\vec{x},t)$, and it is the inflow relative to the propeller since the coordinate system is fixed on the propeller. As described earlier, the potential flow effect and the viscous flow effect are assumed to be independent to each other. Therefore, we assume that the inflow velocity is the sum of the ship wake velocity (viscous flow effect) and the velocities induced by the ship motions (potential flow effect).

$$\vec{U}_{in}(\vec{x},t) = \vec{q}_{in}(\vec{x},t) + \vec{v}_{in}(\vec{x},t) \tag{4}$$

In equation (4), $\vec{q}_{in}(\vec{x},t)$ is the inflow velocity from the ship wake ($\mathbf{U}_E$) and propeller rotation, and $\vec{v}_{in}(\vec{x},t)$ is the inflow velocity due to the ship motions. In this paper, we will only consider the velocities due to pitch and heave motions in the vertical direction (z-direction), and we will also consider the wave induced velocity in the z-direction.

$$\begin{aligned} u_z^P(t) &= \omega_P\alpha(t)x\sin(\omega_P t+\varphi_P) \\ u_z^H(t) &= H_z\cos(\omega_H t+\varphi_H) \\ u_z^w(t) &= A_z e^{k(z+z_0)}\cos[\omega_E t - k(x-x_0)+\varphi_A] \end{aligned} \tag{5}$$

where,

- $u_z^P(t)$ is the inflow velocity from the pitch motion, $\alpha(t)$ is the pitch angle as a function of time, $\omega_P$ is the pitch motion frequency, and $\varphi_P$ is the phase.
- $u_z^H(t)$ is the inflow velocity from the heave motion, $H_Z(t)$ is the heave magnitude as a function of time, $\omega_H$ is the heave motion frequency, and $\varphi_P$ is the phase.
- $u_z^w(t)$ is the wave induced velocity, $A_Z$ and $\varphi_P$ are the velocity magnitude and phase in the z-direction. $\omega_E$ is the encounter frequency of the ship motion. $k$ is the wave number, and $(x_0,z_0)$ is the coordinate of the propeller.

The above inflow velocities from the ship motions can be obtained from the ship motion program.

## 3 The Body Force Method

In this paper, a coupled viscous flow and potential flow method is adopted to compute the propeller/hull interactions. The ship hull flow is solved by the RANS method, and the potential flow boundary element method is used to compute the propeller forces. The propeller forces are then transferred to the body force terms, and the propeller is therefore treated as an actuator disk to provide the momentum changes. This method is named as "body force method" in this paper.

In the presented body force method, the ship hull flow is computed by the viscous flow RANS method, and the commercial software

STAR-CCM+ is used for the computations. Figure 1 shows the ship hull grid and propeller disc for the viscous flow RANS computations. The trimmer grid is mainly used, and multiple layers are used near the hull surface to capture the boundary layers. Different turbulence models are tested, and the Realizable turbulence model is selected for computations. The different wall function parameters and different grid numbers are also investigated for both accuracy and efficiency.

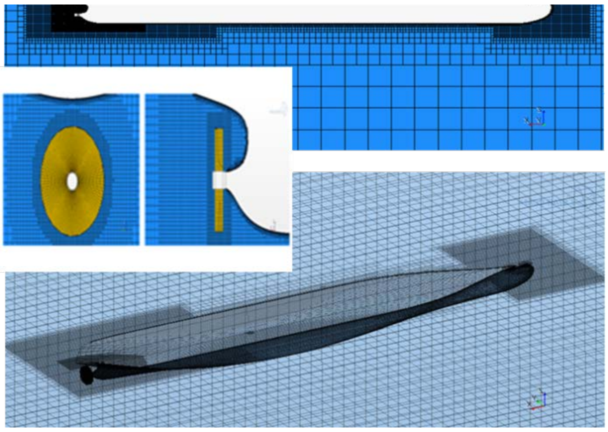

**Figure 1**: The ship hull grid and propeller disc for the viscous flow RANS computations.

The numerical procedure for the presented propeller body force method is as follows:

1. We will first solve the flow field of a “bare hull” by RANS method, that is, a ship hull without the propeller in operation.
2. The velocities at the propeller plane for the bare hull flow are retrieved as the propeller inflow. The propeller boundary element method is then used to compute the propeller flow and forces.
3. The body forces are then computed from the propeller forces.
4. We then solve the ship flow again with the body forces. The flow at the propeller plane is extracted again, and this is the total velocity $\mathbf{U}$ .
5. The circumferential mean propeller induced velocity calculated in the last iteration by potential flow method is denoted by $\bar{\mathbf{U}}_P$ , and it is deducted from the circumferential mean total velocity ( $\bar{\mathbf{U}}$ ) calculated in 4. to get the effective inflow $\mathbf{U}_E$ , which is part of $\vec{q}_{in}$ in equation (4). The circumferential mean value, $\bar{\mathbf{U}}_E$ , will be used in the presented method.

$$\bar{\mathbf{U}}_E = \bar{\mathbf{U}} - \bar{\mathbf{U}}_P \qquad (5)$$

6. The propeller boundary element method is used to compute the propeller flow and forces again.
7. We then repeat 3 to 6 until the solution is converged.

## 4 Computational results

In this section, we will first demonstrate that the body force method can provide the same accuracy as using the RANS method to compute real propeller geometries. Figure 2 shows the flow field computed by both the real geometry and by the body force method. The upper two figures show the side views of propeller flow field downstream, and the lower two figures show the flow field at 0.5 propeller radius downstream (Wei, 2012). One can see that the velocity contours are very similar using two methods, and the major difference is due to the blade effect. We will then use the body force method to compute the interactions between the ship hull and a propeller. Figure 3 shows the velocity contours with and without the propeller, and notice that these are the total velocities. Figure 4 shows the computed circumferential mean axial inflow velocities at the propeller plane along the radial position without propeller (nominal inflow) and with propeller (effective inflow). The differences of two inflows are due to the effect of the propeller/hull interactions. Both Figures 3 and 4 reflect the correct physical phenomenon.

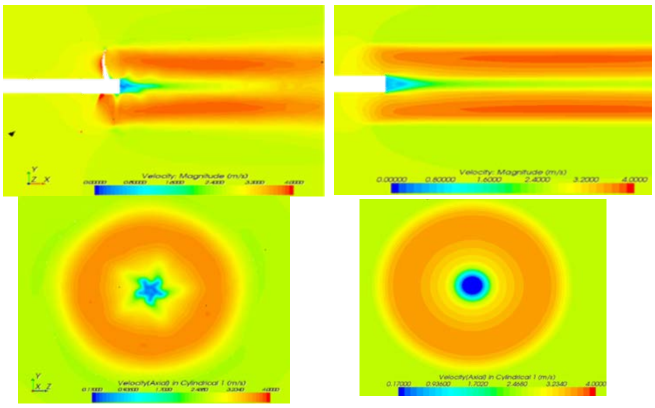

**Figure 2**: The flow field computed by both the real geometry (left) and by the body force method (right).

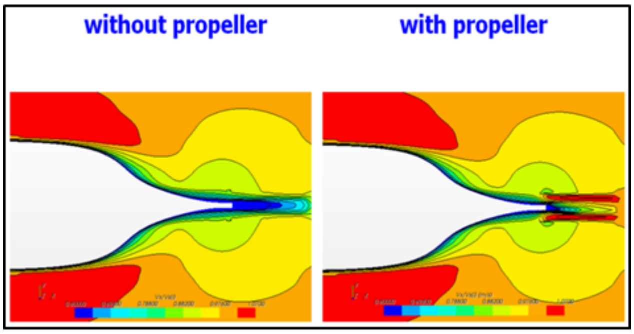


**Figure 3**: The velocity contours with and without the propeller computed by the presented method.

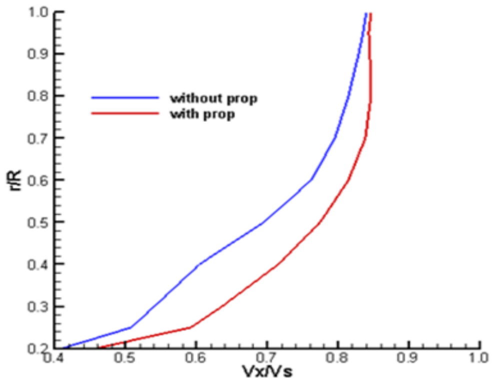


**Figure 4**: The computed axial inflow velocity without propeller (nominal inflow) and with propeller (effective inflow).

We then demonstrate the computational results of ship motion effects. A ship in the pitch motion is used for the computations, and the propeller inflow velocities are computed from a ship motion program. The frequency of this pitch motion is 0.5 ( $\omega_P = 0.5$ ), and the maximum vertical velocity due to the pitch is 10% of the ship speed. Since the encounter frequency of the incoming wave is far smaller than the propeller rotational frequency, for a typical container ship propeller with a rotational frequency 12.6 (*rps*=2.0), this propeller will rotate more than 25 revolutions in one wave period. Therefore, for demonstration purpose, the propeller rotational frequency is assumed to be very low as 2.5 here. The propeller unsteady flow boundary element method is then used to compute the propeller forces. Figure 5 shows two results, one is the computed thrust in ship wake only (marked by "prop. only"), and the other one is to consider the ship pitch motion (marked by "with pitch"). The effect of pitch motion is obvious by comparing two curves. In order to understand the unsteady flow effects, we first use the quasi-steady flow approach on the pitch motion effect, and the results are shown in Figure 6. We can see that the quasi-steady solutions are almost the same as the unsteady solutions, and this conclusion is the same as that by Faltinsen. We then use the quasi-steady flow approaches on both the ship wake and ship motion effects, and the results are shown in Figure 7. The differences are apparent between the quasi-steady flow solution and the unsteady flow solution. Therefore, we can conclude that the unsteady flow effect due to the ship wake is more important than that due to the ship motion.

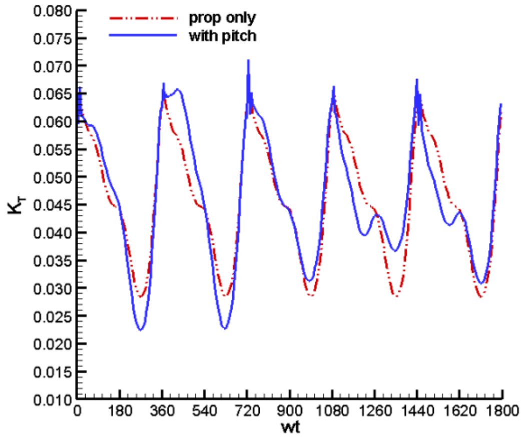


**Figure 5**: The computed propeller thrusts. "prop. only" is the computed thrust in the wake only, and "with pitch" is the computed thrust considering the ship pitch motion.

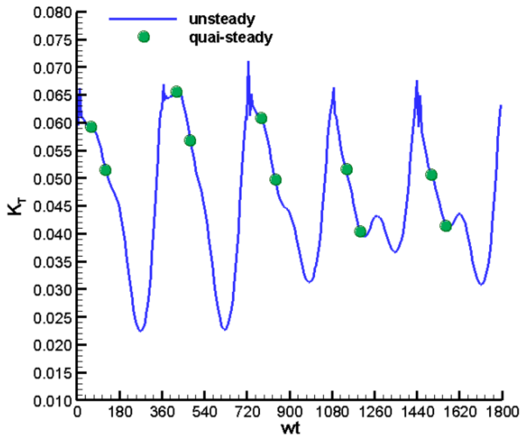


**Figure 6**: The computed propeller thrusts by using the quasi-steady flow approach on the pitch motion effect.

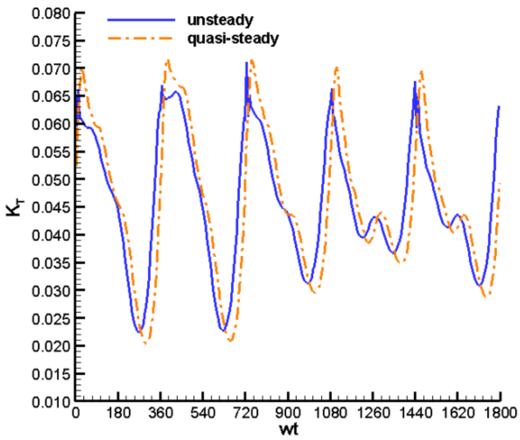


**Figure 7**: The computed propeller thrusts by using the quasi-steady flow approaches on both the ship wake and ship motion effects.

## 5 Conclusions

In this paper, both the potential flow and viscous flow computational methods and their results are presented for the evaluation of the effect of Ship motion on propeller performance. It is shown that the body force method can successfully simulate the interaction between the ship hull and a propeller. Computational examples are also demonstrated for investigating the effect of ship pitch motion on the propeller performances. From the computational results, we found that the effect of pitch motion on propeller performance is obvious, and the unsteady flow effect due to the ship wake is more important than that due to the ship motion.

In this presented work, we have established the first step to integrate ship motion computational method, the propeller boundary element method, and the viscous flow RANS method to evaluate the propeller performance in seaway. More investigations are necessary to verify this approach and its computational results in the future.

## References

Ando, J., Kataoka, K., and Nakatake, K., "Free Surface Effect on the Propulsive Performance of a Ship (2nd Report)", West Japan Soc. Nav. Arch. Trans. (77), pp. 9-28, March, 1989

Ando, J., Shiota, H., Kataoka, K., and Nakatake, K., "Free Surface Effect on the Propulsive Performance of a Ship (3rd Report)", West Japan Soc. Nav. Arch. Trans. (79), pp. 13-20, March, 1990

Chuang, Z. and Steen, S., "Prediction of Speed Loss of a Ship in Waves", Second International Symposium on Marine Propulsors (smp'11), Hamburg, Germany, June 2011

Faltinsen, O.M., "Prediction of Resistance and Propulsion of a Ship in a Seaway", Proc. 13th Symposium on Naval Hydrodynamics, 1980, Tokyo, Japan

Journée, J.M.J., "Prediction of Speed and Behaviour of a Ship in a Seaway", Report 0427-P, 1976, Delft University of Technology, Ship Hydromechanics Laboratory, Delft,The Netherlands

Journe, J.M.J., "Motions, Resistance and Propulsion of a Ship in Regular Head Waves", Report 0428, 1976, Delft University of Technology, Ship Hydromechanics Laboratory, Delft, The Netherlands

Kashiwagi,M., Sugimoto, K., Ueda, T., Yamasaki, K., Arihama, K., Kimura, K., Yamashita, R., Itoh, A. and Mizokami, S., "An Analysis System for Propulsive Performance in Waves", Journal of the Kansai society of naval architects, No. 241, 2004

Naito, S. and Nakamura, S., "Open Water Characteristics and Load Fluctuation of Propeller at Racing Condition in Waves", Journal of the Kansai society of naval architects, Japan, No. 192, 1979

Nakamura, S., Naito, S. and Inoue, R., "Open Water Characteristics and Load Fluctuation of Propeller in Waves", Journal of the Kansai society of naval architects, Japan, no.159, 1975

Nakatake, K., Oda, K., Kataoka, K., Nishimoto, H. and Ando, J., "Free Surface Effect on the Propulsive Performance of a Ship (1st Report)", West Japan Soc. Nav. Arch. Trans. (72), August, 1986, pp.129-139

Paik,B.-G., Lee, J.-Y., and Lee, S.-J., "Effect of Propeller Immersion Depth on the Flow Around a Marine Propeller", Journal of Ship Research, 52 (2), June 2008, pp. 102-113

Stuart, D.J. and Boswell, R.J., "The Effects of Hull Pitching Motions and Waves on Periodic Propeller Blade Loads", Proc. 14th Symposium on Naval Hydrodynamics, 1982, Michigan, U.S.A.

Stuart, D.J. and Wang, H.-C., "Propeller Cavitation Prediction for a Ship in a Seaway", CRDKNSWC/HD-1292-01, Aug. 1996

Wei, W.-C., “The Influence of the Propeller Loading Distributions to the Propulsive Efficiency”, Master thesis, Nation Taiwan Ocean University, 2012